A GIS-based Analysis on the Capacity and Feasibility of Pumped Hydropower Storage Facilities in Tibet

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Abstract

Solar and other forms of renewable energy are critical to our transition to green energy infrastructure. However, intermittent output and uneven temporal demand significantly degrade operational efficiency. Pumped hydroelectric storage (PHS) provides an effective load balancing solution to stabilize intermittent differences in supply and demand. However, PHS facilities are not only expensive to construct, but also have stringent geographical requirements. As such, this study uses a GIS-based method to assess PHS feasibility and potential in Tibet, a remote and yet-to-be-developed region with the second highest solar radiation in the world. With access to fossil fuel resources limited and a fragile natural environment, Tibet would seem to benefit the most from PHS and solar energy developments. The objective of this study, therefore, is to identify potential locations for construction of PHS facilities and determine their feasibility using geographical, infrastructural, and basic economic demand factors. Two scenarios for PHS systems are considered: lake-lake (S1), and river-lake (S2). Based on geographical factors, the results showed that feasible PHS potential in Tibet was approximately 1273.1 GWh and 172 GWh under S1 and S2 respectively. S1 yielded 25 sites of mostly marginal and poor qualities, while S2 yielded two sites of high quality. When factoring basic infrastructure and economic demand factors, the S2 sites showed high feasibility scores. The results show the limitations on the implementation of PHS in remote regions and suggest that alternative methods of energy storage may be needed.

Introduction

Ever since the dawn of the industrial age, economic growth has relied upon energy consumption, leading to greenhouse gas emissions. However, we may be approaching the limit of this practice. According to the IPCC, global temperatures have risen approximately 1.0 degrees Celsius since pre-industrial levels, and continued warming at this rate may have devastating consequences to both human and natural systems (IPCC, 2019).

Renewable energy provides an effective solution to eliminate greenhouse gas emissions while satisfying our growing energy demand. As a result, they have also become one of the fastest growing energy markets in the world (IEA, 2019). According to the *BP Statistical Review of World Energy*, the consumption of renewable energy, which includes wind, solar, geothermal, biomass and waste, has been growing with a compound annual growth rate of 16.1% between 2005 and 2015 (BP, 2018).

However, not all forms of renewable energy are readily available. While hydropower and geothermal energy can be tapped at almost any time, solar, wind, wave and tidal energy are intermittent sources that depend significantly on local and regional weather and climatic variations (Chen et al., 2009; Evans et al., 2012). In other words, we cannot control the availability of these intermittent energy sources. If not used immediately, the energy is lost potential. This unpredictability is further complicated by the timing imbalance between peak demand and renewable energy production. Known notoriously as the "duck curve," this imbalance describes the mismatch between the time of peak solar generation, usually during the day, and the time of peak demand, which is typically during the evening.

Energy storage systems (ESS) provide the most promising solution to this inherent problem in renewable power generation. By converting electrical energy into a form that can be stored and converted back to electrical energy when needed, ESS has significant potential to redistribute energy according to average demand, a process known as load-balancing (Chen et al., 2009). As a result, it is widely agreed that the availability of energy storage can increase the penetration of intermittent renewable generation greatly (Barton and Infield, 2004). In addition to renewable energy, ESS also improves the operating efficiency of traditional power plants.

Because maximum demand often lasts as short as a few hours each year, many power plants are required to operate for only short periods each year, which greatly reduce their efficiency (van der Linden, 2006). The availability of large-scale ESS, therefore, allow the generation capacity to meet the average demand as opposed to peak demands, improving system efficiency by as much as 40% (van der Linden, 2006). Today, there are four main forms of ESS: mechanical, electrical, thermal, and chemical (Evans et al., 2012). While each has its advantages and disadvantages, the most prevalent and mature technology is the pumped hydroelectric storage (PHS) system, a form of mechanical ESS that takes advantage of gravitation potential energy (Evans et al., 2012).

PHS is the most widely implemented bulk ESS, currently accounting for at least 95% of all utility-scale energy storage in the United States and up to 99% in the world, with a total capacity exceeding 125 GW (Barbour et al., 2016; U.S. Department of Energy, 2019). As seen in Figure 1, the energy storage capability the system is driven by the height differences (known as "head") between the upper and lower reservoirs as well as their volumes. During times of greater supply than demand, PHS converts the excess energy into storage by pumping water from the lower reservoir to the upper. When demand exceeds supply, the process reverses, and energy is produced much like a conventional hydroelectric plant. While close-looped systems often require two separate reservoirs, open loop systems allow rivers, underground cavities, and even the ocean to substitute as the lower reservoir (Chen et al., 2009).

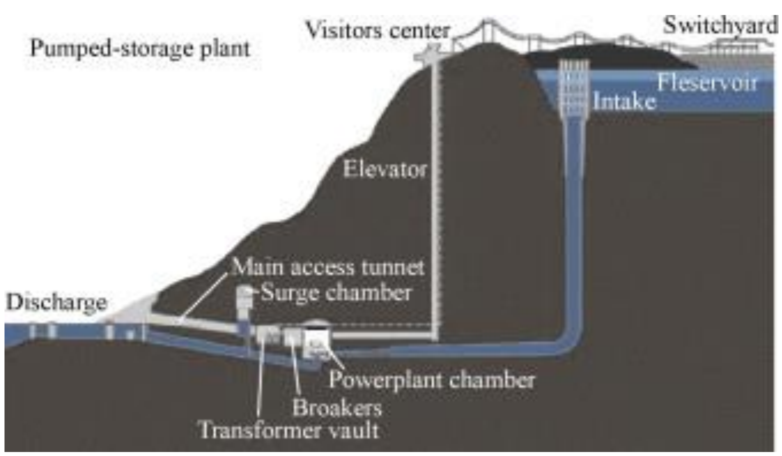

Figure 1. *A schematic diagram of a typical PHS facility (Chen et al., 2009).*

The primary advantages of PHS facilities lie in its large capacity, long storage period, long system lifetime, high efficiency, and relatively low capital cost per unit of energy (Chen et al., 2009). With capacity ratings on the order of gigawatts and an average lifetime of 50 to 60 years, the large storage potential of PHS arises from naturally-occurring high head differences between the two reservoirs as well as the large volume of the upper reservoir (Ibrahim et al., 2008; Barbour et al., 2016). Efficiency, meanwhile, is reduced only by evaporation and conversion losses, resulting in a total generation efficiency of between 65% to 85% (Ibrahim et al., 2008; Chen et al., 2009).

These advantages altogether result in PHS being not only the most prevalent but also the oldest form of utility-scale ESS. While the first use of PHS principles occurred as early as the 1890s in Italy and Switzerland, the first true PHS facility was constructed in 1929 in New Milford, CT, as shown in Figure 2, "to store reserve power for daily peak loads" (Popular Science, 1930; Chen et al., 2009). By 1930s, reversible turbines that act both as pumps and generators became available (Barbour et al., 2016). However, as Figure 3 shows, large-scale PHS development did not take off until the 1960s and 70s. This is because, for regions including Europe, Japan, and the U.S., the development of PHS was a direct result of the increased capacity of nuclear power, which must operate at full capacity and thus mandated a storage system for the excess energy it produced (Barbour et al., 2016). Around the 1990s, concerns of nuclear safety, as well as the environmental damages from dams, slowed PHS growth in Europe and the U.S., and it was not until the recent rise of renewable energy did demand for PHS facilities rise again.

One outlier to the trend above is China. PHS development in China began as early as the 1960s, but it remained dormant until the 1990s, after which it skyrocketed. Fast economic growth put strains on the coal-dominated energy system (Ming et al., 2013). Compounded with the desire to increase renewable energy in the power structure, China has built some of the largest PHS facilities to compensate peak and valley load variations (Chang et al., 2010). In fact, out of the 67 PHS facilities around the world with more than 1 GW in capacity, 16 belongs to China, representing almost 20 GW of capacity. The State Grid Corporation of China states that the country is currently constructing a further 21.75 GW of PHS capacity (State Grid, 2016).

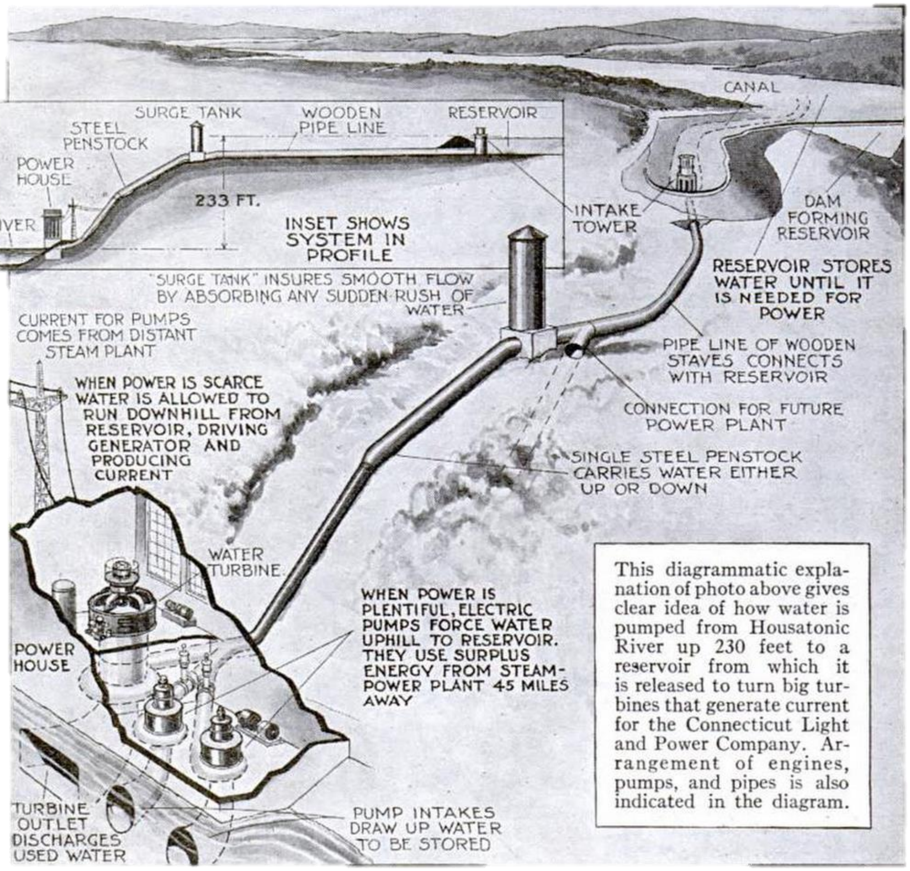

***Figure 2**. An illustration of the original PHS facility (now known as "Rocky River Pumped Storage Hydraulic Plant") in New Milford, CT (Popular Science, 1930).*

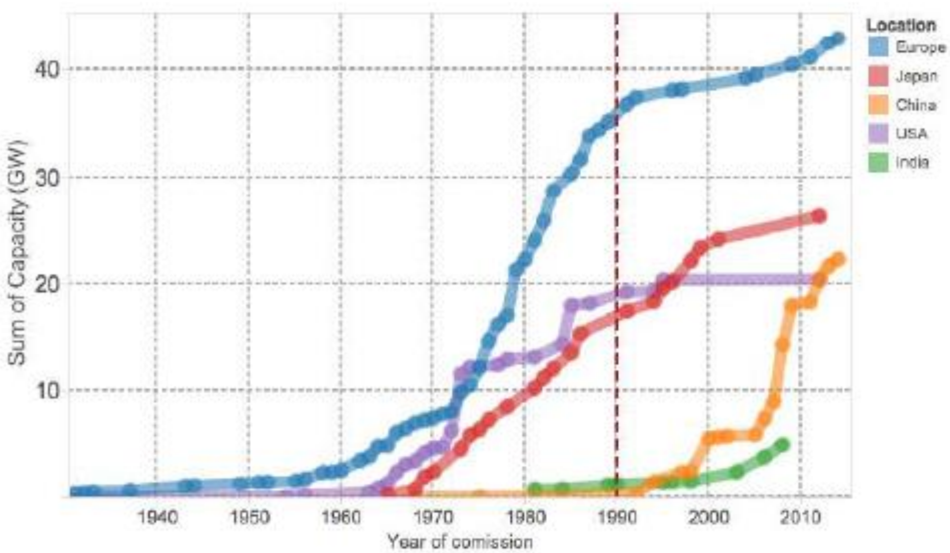

***Figure 3**. Total PHS capacity of key regions around the world (Barbour et al., 2016).*

Despite its prevalence and renewed demand, there are major challenges to the continued development of PHS. First, it is widely agreed today that the most economically feasible and environmentally friendly approach to developing PHS is to convert existing water bodies (i.e., lakes) into upper and lower reservoirs (Ibrahim et al., 2008; Fitzgerald et al., 2012; Gimeno-Gutiérrez and Lacal-Arántegui, 2015). However, the challenge of this approach lies in the scarcity of two large reservoirs with a large head (Ibrahim et al., 2008; Chen et al., 2009; Evans et al., 2012). While the use of open-looped systems such as rivers to substitute the lower reservoir has provided more options for PHS construction, site selection nevertheless remains a challenge.

This study, therefore, aims to develop a systematic process to assess total PHS potential and identify suitable sites for PHS construction in a given region. For this purpose, GIS-based geospatial analysis offers a useful and cost-effective tool for the initial screening (Fitzgerald et al., 2012; Gimeno-Gutiérrez and Lacal-Arántegui, 2015; Lu and Wang, 2017). Previous studies have already demonstrated the capability of using GIS-based methods to predict and locate hydropower potential (Larentis et al., 2010). In addition, Connolly et al. (2010) developed a GIS-based model based on digital terrain maps to determine suitable sites for PHS. However, both studies are computationally intensive, limited in terms of geographical area, and involve constructing new reservoirs (Larentis et al., 2010; Connolly et al., 2010). Fitzgerald et al. (2010) subsequently incorporated a scalable methodology that involves the use of existing reservoirs, and Gimeno-Gutiérrez and Lacal-Arántegui (2015) refined it further and tested it against existing PHS facilities in Europe for accuracy. However, these studies have two main shortcomings. First, they do not include open-looped systems that involve, for example, a river. Second, none involve quantitative and qualitative analyses on economic and infrastructural feasibility. As such, this study aims to test existing methodologies on closed-loop systems, introduce open-looped river to reservoir scenarios, and incorporate basic feasibility studies of the results.

Study Area

The Tibetan Plateau is chosen for this study for many reasons. First, the remoteness of the Tibetan Plateau, its high elevation, and the lack of efficient transportation infrastructure pose unique challenges to fossil fuel access. Because this access is limited, biomass sources such as manure, firewood, and crop residues make up two-thirds of Tibet's total energy use (Liu and Lucas, 2014). However, these sources often involve pollutants that degrade Tibet's natural environment, which is particularly fragile and sensitive (Liu and Lucas, 2014). As such, a fast transition to renewable energy is critical to preserve ecosystem health.

Second, energy security and electrification in remote regions like the Tibet Autonomous Region (TAR) are critical to China's national security (Luo and Guo, 2013). While this study does not in any way comment on the international and regional politics concerning Tibet, the fact remains that currently, the region is under direct control by the Chinese government. Since 2005, renewable energy development has been one of the top priorities of China (Zeng et al., 2013). Many studies, reports, and news articles have acknowledged the rapid rise of renewables in the country. According to *The BP Statistical Review of World Energy*, China increased its renewable generation by 25 mtoe in 2017 alone, a country record which became the second largest contribution to global primary energy growth from any single fuel and country (BP, 2018). Besides, as mentioned earlier, China is also rapidly exploiting and constructing new PHS resources. Given these favorable tailwinds from the government, further development of both renewable and PHS seem very likely.

Third, the Tibetan Plateau has abundant natural resources for both renewable energy and PHS development. As discussed earlier, PHS can effectively smooth the inherent output variability of intermittent renewable energy sources such as wind and solar. Figure 4 shows that the Tibetan Plateau has not only significant wind potential, but also the highest solar potential in the nation and second worldwide, with average solar radiation reaching 7000 MJ/m^2 year (Zeng et al., 2013; Lu and Wang, 2017). Also, Figure 5 shows that the greater Tibetan region has the majority of the water resources of China, with more than 1,500 lakes (Ming et al., 2013; Lu and Wang, 2017). Given the abundance of these resources, Tibet is perhaps the most suitable region to exploit PHS development and test the parameters and methodology of this study.

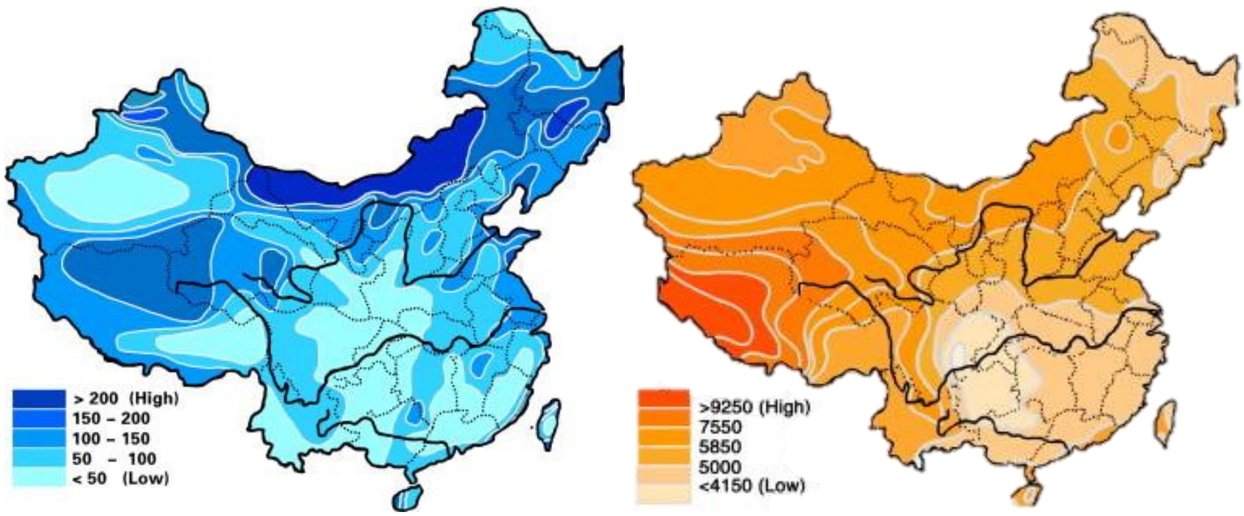

Figure 4. *Distribution of wind (W/m²) and solar (MJ/m² year) resource in China (Zeng et al., 2013).*

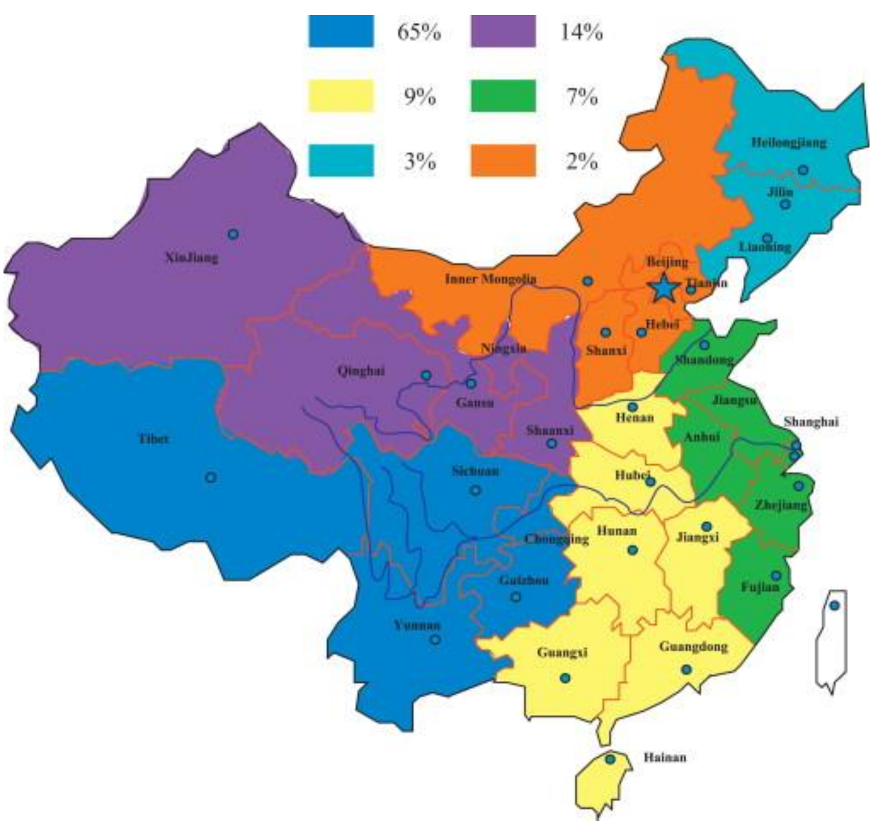

Figure 5. *Distribution of water resources in China (Ming et al., 2013).*

Methods

Because this study uses GIS-based analyses, geographical data must be obtained. For this study, the boundary of Tibet is technically defined as the border of the TAR officially recognized by the Chinese government (Figure 6). The author acknowledges that this boundary may involve disputed regions. However, for simplicity and accuracy of the methodology, water bodies within the disputed regions are included in the analysis. This study uses ArcGIS 10.4.1 as the primary software to carry out relevant geospatial analyses. All the algorithms applied can be found in the ArcToolbox with appropriate 3D Analyst and Spatial Analyst licenses. The study also uses ENVI software for processing relevant elevation data as well as Google Earth as a proxy for ground truth assessments of potential PHS sites.

Hydrologic data

Lake data of the Tibetan Plateau was obtained from Wan et al. (2016). Using sensors from China's GF-1 WFV (Wide Field of View Cameras), Wan et al. extracted water bodies manually to avoid errors and uncertainties in various automatic extracting methods (Wan et al., 2016). The result represents the best publicly available dataset of lakes on the Tibetan Plateau (Figure 6).[1] For this study, any lake whose boundary extends beyond the study area is eliminated from the study.

River data of major perennial rivers on the Tibetan Plateau is obtained from the China Data Center of the University of Michigan and accessed from the Stanford EarthWorks library. The data is downloaded as a polyline shapefile (Figure 6) and exported into ArcMap.

DEM data

Digital elevation model (DEM) data is obtained from version 2 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM) dataset, accessible from the USGS EarthExplorer database. The data comes in the form of 1° by 1° tile with a spatial resolution of 1 arc-second, which is sufficient for the calculation of head

[1] data can be accessed at http://dx.doi.org/10.6084/m9.figshare.3145369

differences between the two reservoirs (Lu and Wang, 2017). A total of 286 tiles covering the study area was downloaded and stitched together using ENVI. While ASTER GDEM is notorious for artifacts, especially in mountainous terrains, the overall quality of the dataset for the study area is excellent, with only one concentrated area around eastern TAR showing minor artifacts (Figure 6).

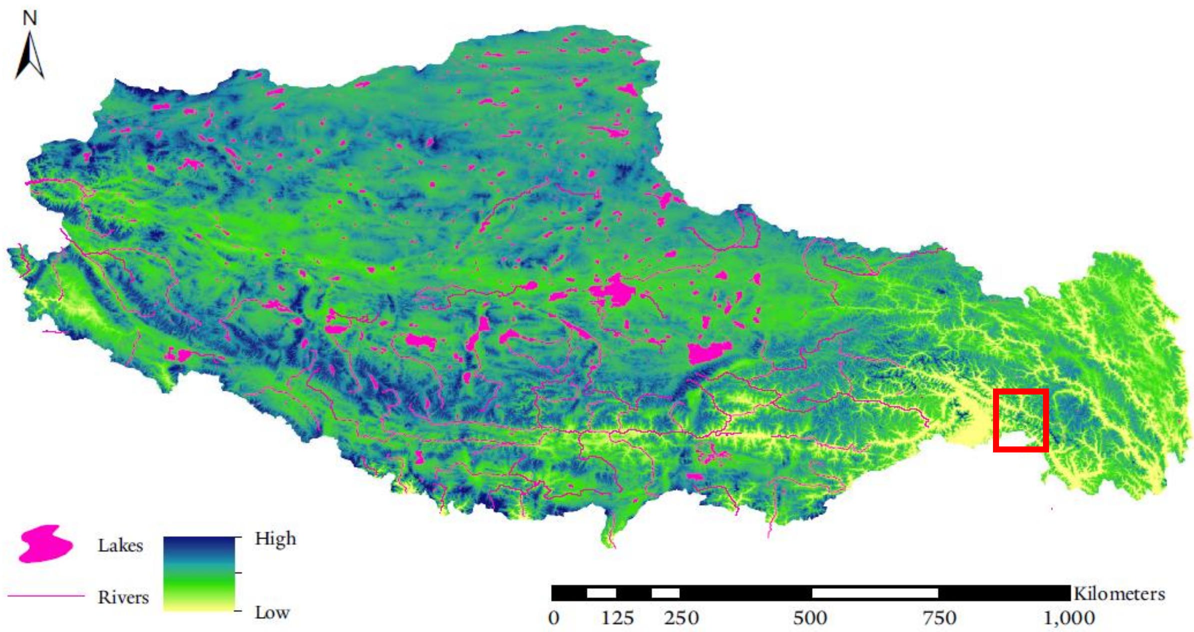

Figure 6. *The boundaries of the study area with DEM and hydrologic data. The highlighted area in red contain DEM artifacts. However, the overall quality of the data is excellent.*

Infrastructure and population data

Infrastructure and population data are gathered to assess the feasibility of potential PHS sites. The availability of road and existing grid infrastructure is critical to the economic feasibility of PHS development by facilitating construction and grid connection while significantly lowering costs (Lu and Wang, 2017). However, while road data was obtained from the China Data Center (accessed through the Stanford EarthWorks library), no public grid infrastructure data was found, which would have preferably included location of substations, transmission lines, and existing power plants. Instead, population density is used as a proxy for grid infrastructure, as one expects grid infrastructure to be more mature near urban areas. Data for the population is also sourced from the China Data Center based on a census from 2000. Figure 7 shows the road and population data of the study area. Population density is converted from point vector to raster format by interpolating 723 individual township census data points using nearest neighbor sampling.

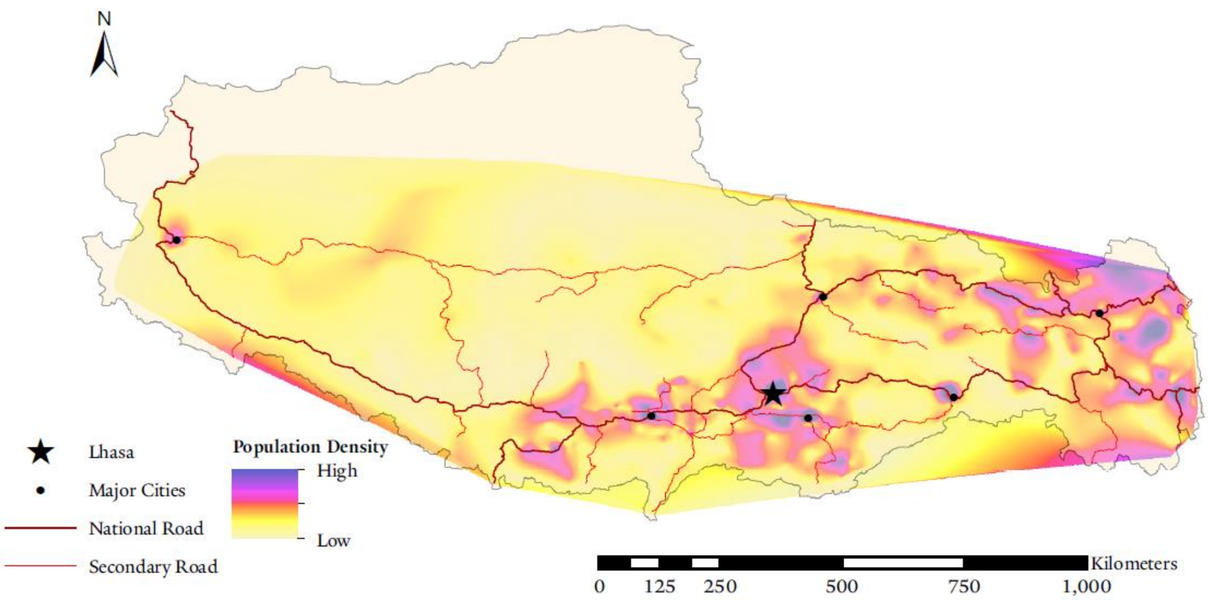

Figure 7. *Infrastructure and population data of the study area. National roads and secondary roads do not contain meaningful differences. Population density is interpolated from 723 individual township census data using nearest neighbor sampling.*

PHS site selection criteria

Because the most economically feasible and environmentally sensitive approach to constructing PHS facilities is to use existing water bodies, two scenarios for potential PHS sites are considered for this study:

1. Finding potential PHS sites by connecting two existing lakes (S1).
2. Connecting an existing lake to a river, which acts as an open-looped lower reservoir (S2).

Constraints placed on both scenarios are outlined in Table 1. They are based on prior GIS-based studies on PHS potential (Fitzgerald et al., 2012; Gimeno-Gutiérrez and Lacal-Arántegui, 2015; Lu and Wang, 2017). The maximum horizontal distance between two reservoirs was set at 10 km. While this may seem rather long, it is worth noting that the Yamdrok Hydropower Station, the only PHS facility currently operating in the study area, has a horizontal distance of 9 km. Minimum lake surface area is set at 10km^2 to eliminate small lakes, as these may be subject to seasonal fluctuations in volume, and may even disappear over time. However, Lei et al. (2017) noted that most lakes in Tibet have been growing steadily in size due to increased glacier melting from global warming. Minimum head to distance ratio is set to 0.1 to select for PHS systems with high potential energy.

Table 1. *Constraints for PHS site selection.*

Criteria	**Value**
Maximum Distance	10 km
Minimum Lake Surface Area	10 km^2
Minimum Head to Distance Ratio	0.1

S1: Connecting two existing reservoirs

For this scenario, the primary objective is to locate pairs of lakes within 10km of each other that have sufficient head differences to result in a minimum head to distance ratio of 0.1. Figure 8 describes the methodological flowchart for the analysis similar to an automated GIS model. First, elevation data from ASTER GDEM was added to the lakes data through the "Add Surface Information" tool, which calculates the mean elevation of all the pixels within a lake. Then, we used the "Generate Near Table" tool to find all possible pairings of lakes within 10 km of each other. By using the "XY to Line" tool, we converted the distance between two lakes into a polyline format. After calculating the distance and slope, the connecting lines were manually scrubbed to eliminate duplicate and erroneous pairings. Finally, by using the "Select Layer by Location" tool, we clipped lake pairs that are tangential to the connecting lines between them. This process resulted in a shapefile of lakes that fit within the constraints of Table 1 as well as lines that connect each pair of lakes.

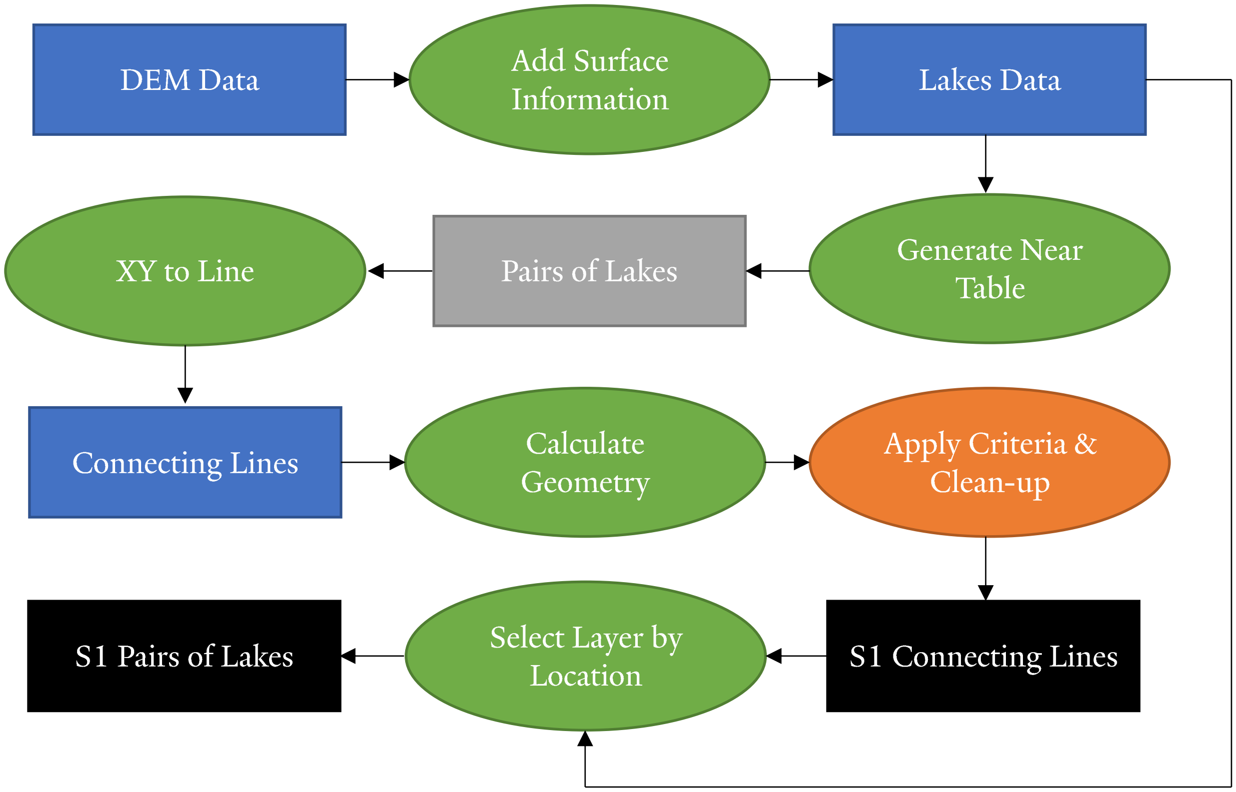

Figure 8. *Methodological flowchart for S1. In general, squares indicate data, and circles indicate processes. Blue represents initial and intermediary spatial data, green represents tools and algorithms used in the analysis, gray represents intermediary non-spatial data, orange represents manual edits, and black represents the final output data. The connecting lines refer to the shortest linear line between two lakes.*

S2: Connecting existing reservoirs to nearby rivers

Compared to S1, S2 is more methodologically complicated because it involves both rivers and lakes. Figure 9 shows the methodological flowchart for S2. The objective is the same as S1, except rivers were substituted as lower reservoirs. The process also begins by adding elevation data to lakes and generating a near table between any lake and river that are within 10 km of each other. The resulting XY coordinate pairings were converted into connecting lines, and erroneous pairings were eliminated. At this stage, however, because elevation data has not yet been added into rivers, we could not apply all of the constraints in Table 1. Also, unlike a lake, rivers typically have varying elevations that decrease further downstream. As such, calculating the exact elevation is critical to determine the head accurately. To achieve this, we converted the connecting lines into endpoints, added elevation data to the endpoint on the river, and spatially joined the elevation data back to the connecting lines. With elevation data of both the river and the lake added to the attributes of connecting lines, head and slope could then be calculated. Those pairings that did not fit within the constraints were eliminated.

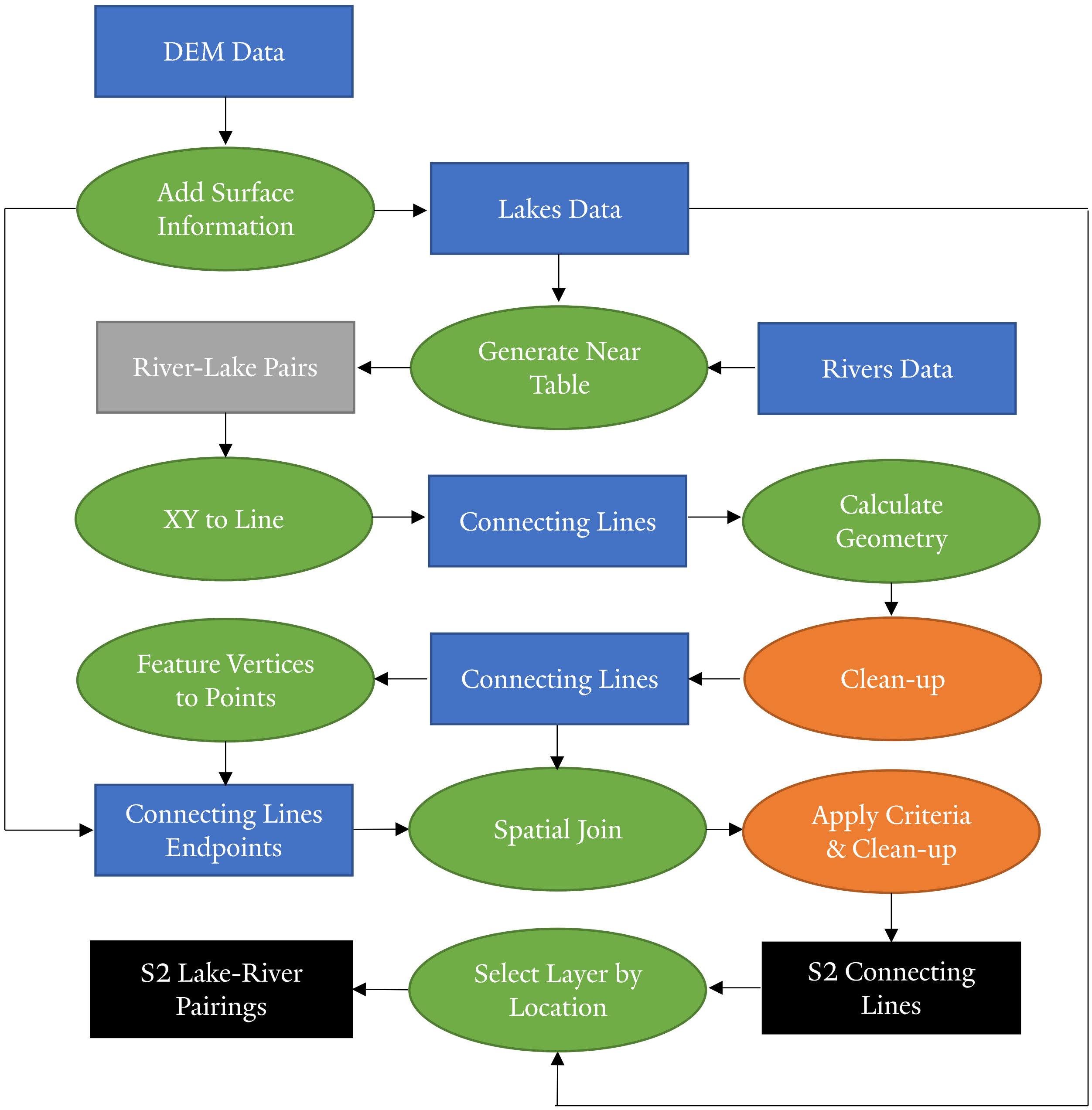

Figure 9*. Methodological flowchart for S2. Compared to S1, S2 involve an extra series of steps primarily due to the need to add elevation data to both lakes and rivers in order to calculate the slope. Thus, the first manual step (orange) scrubs the data for erroneous results, while the second applies the minimum slope.*

Calculation of PHS potential

With a list of all possible pairings under S1 and S2, the potential PHS capacity was calculated. Potential PHS capacity is defined as the hydraulic energy available in a body of water (Fitzgerald et al., 2012; Lu and Wang, 2017):

$$E = \rho g h V \mu$$

where:

E = energy available (Joules)
ρ = water density (1019 kg/m^3)
g = gravitational acceleration (9.81 m/s^2)
V = volume of the upper reservoir
μ = generation efficiency (assumed 90%)

However, because the accurate calculation of the reservoir volume requires information regarding its depth and geometry, we can only estimate volume by assuming that:

$$V = Ad$$

where:

A = surface area
d = average depth (assumed 20m, which corresponds to the average reservoir depths estimated by Gimeno-Gutiérrez and Lacal-Arántegui, 2015, and Lu and Wang, 2017).

To measure the effectiveness of the two assumptions of efficiency and average depth on PHS capacity, sensitivity analyses on efficiency and average reservoir depths were performed.

Feasibility analysis

The second part of this study involves a qualitative analysis of the feasibility of potential PHS sites. It is further divided into two parts. The first involves using Google Earth to holistically assess the site's geographical features to determine its quality. As mentioned earlier, Google Earth is a useful tool as a proxy for ground truth assessments, especially in remote regions like the Tibetan Plateau. For each potential PHS site, we assigned a categorical value to its quality: Good (3), Marginal (2), and Poor (1).

Second, we converted the road and population density data into a score map. For road data, five buffer rings of 50 km each were created, with the closet ring bearing a score of 5 and the furthest 1. For population density, the interpolated map was reclassified into five equal zones, with the densest areas bearing a score of 5 and the least dense a score of 1. Since the population data does not cover the entire study area, those PHS sites outside the coverage area were not included in the feasibility analysis. The scores of population density and road proximity are then summed to form a single raster score map, shown in Figure 10.

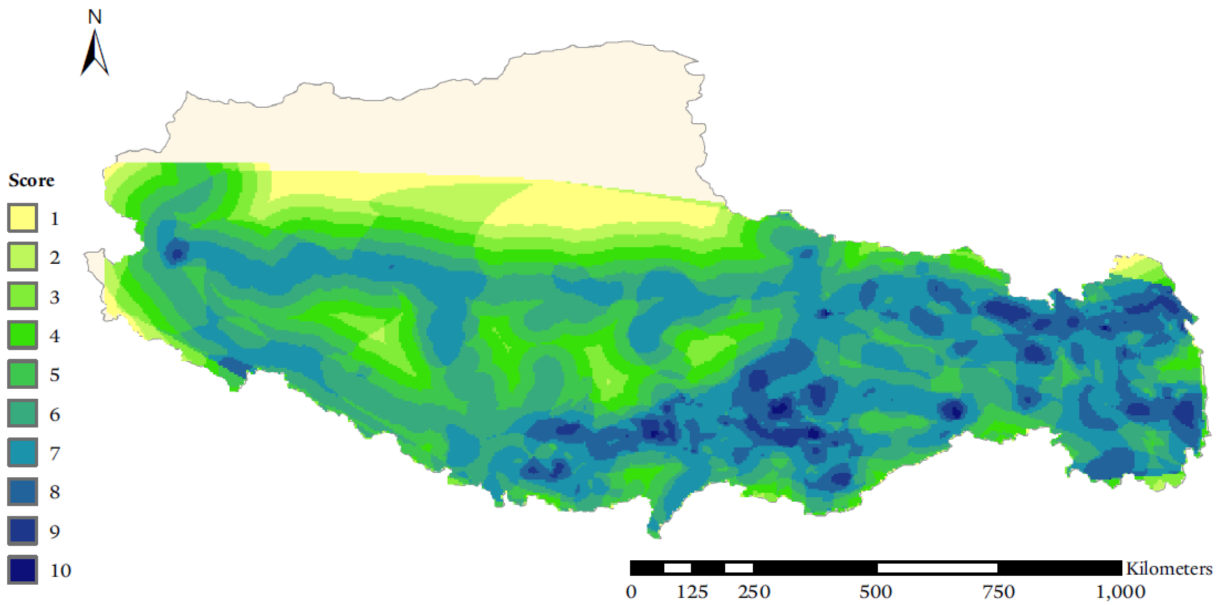

Figure 10. *Score map of the study area for feasibility analysis. 10 represents the most feasible, while 1 represents the least. Areas not covered by this score map is excluded from the analysis. This score map is composed of 1) five 50 km buffer rings around roads with scores from 1 to 5, and 2) population density sorted into five classifications also with scores from 1 to 5. The two sets of data are then converted into raster form and summed to create one raster image with ten possible scores.*

Results

PHS potential under S1

The methodology outlined in Figure 8 resulted in 296 possible lake pairings within a 10 km horizontal distance. Despite having more than 1500 lakes in the region, only 25 pairings had a head to distance ratio of greater than 0.1. This represents a total PHS capacity of 1273.1 GWh under default assumptions. The spatial distribution of these sites is mostly in central and northern Tibet.

Using Google Earth's 3-D imagery, we determined that seven out of these 25 potential sites were of poor quality, and the quality of the remaining 18 were determined to be marginal (Figure 11). None was determined to be of good quality primarily because of the small magnitudes of head and distance separations between the upper and lower reservoirs. Most marginal reservoir pairs were also either too close or even connected (Figure 12). Poor quality rivers were mostly duplicate or erroneous results.

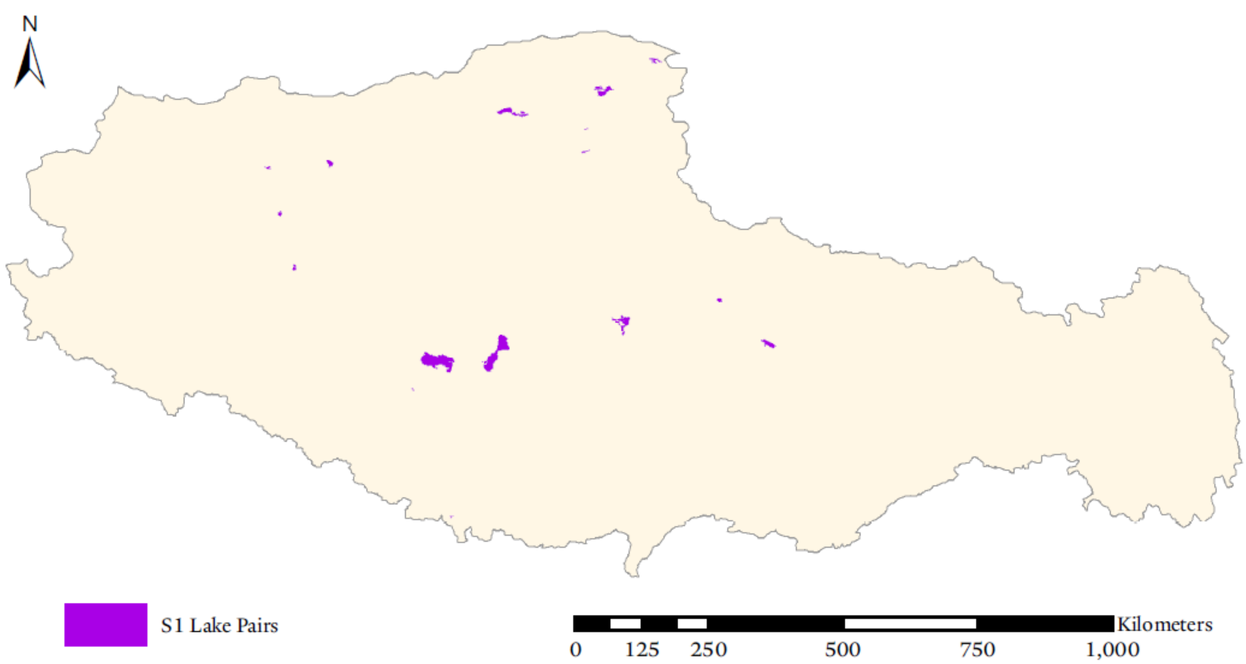

Figure 11. *Results of potential PHS sites under S1 that are at least marginal quality.*

Figure 12. *Examples of S1 pairings deemed marginal in quality. Both pairs fit the criteria in Table 1. While it is technically possible to engineer pairings like these into PHS facilities, the process would involve dramatic alterations of the hydrology and the surrounding environment. This study aims to avoid such alternations and disturbances.*

PHS potential under S2

The methodology for S2 outlined in Figure 9 resulted in a total of 46 possible lake-river pairings within 10km horizontal distance. However, only three attained a head to distance ratio of at least 0.1 (Figure 13). Yet, these three results represent a total PHS capacity of 22 TWh, a surprisingly large capacity. This is mainly because one of the upper reservoirs, the Yamdrok Lake, which incidentally happens to be where the only existing PHS facility in the region is located, has a total surface area of 548 km^2. Compounded with a head of 814 m to the nearest river, this reservoir has the single largest capacity in this study. If we subtract the capacity of this reservoir from the results, the remaining two systems have a total capacity of 172 GWh.

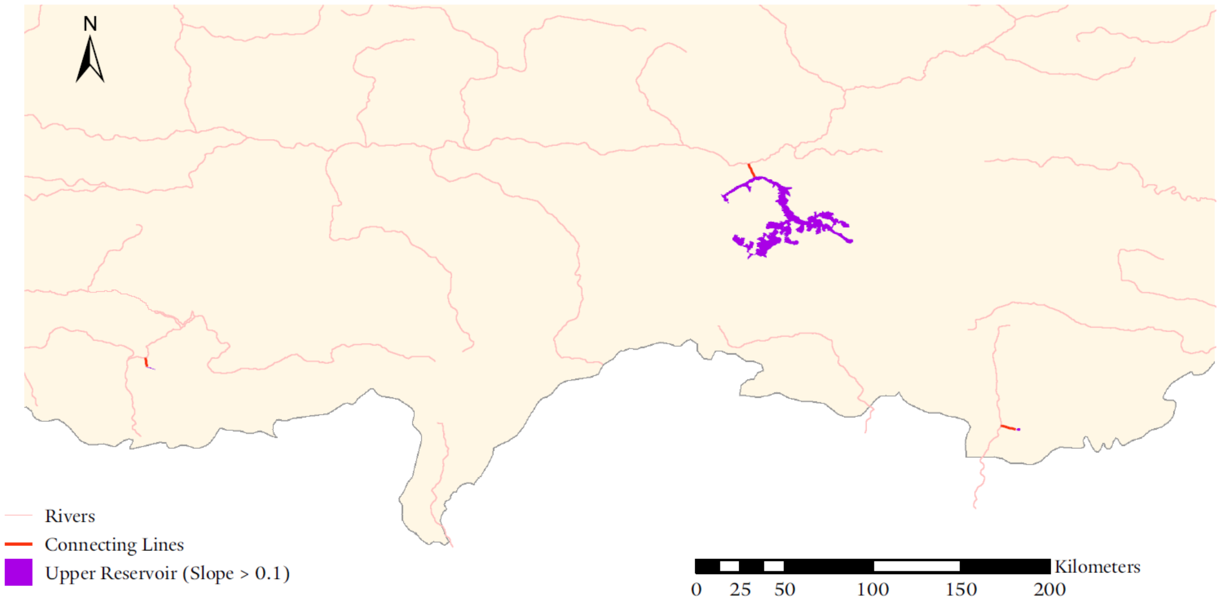

Figure 13. *Three potential PHS sites under S2. The large reservoir in the center is the Yamdrok Lake. Calculations indicate that the Yamdrok lake alone has a capacity of almost 22 TWh.*

The Google Earth images indicate that both sites (excluding the one involving Yamdrok Lake) were of good quality. Figure 14 shows a 3-D satellite image of the potential site southeast of Yamdrok, while figure 15 shows that of the site southwest. Both sites are characterized by high head differences, as well as natural drainage lines to the nearby river, which can be easily dammed and converted to PHS facilities.

The score map in Figure 10 indicates that the three results had an average feasibility score of 7.1. Yamdrok had an average score of 7.4 across all its pixels, the site southeast had a score of 6.0, and the site southwest had a score of 7.7. In comparison, the average score of the 18 marginal sites in S1 is 5.1.

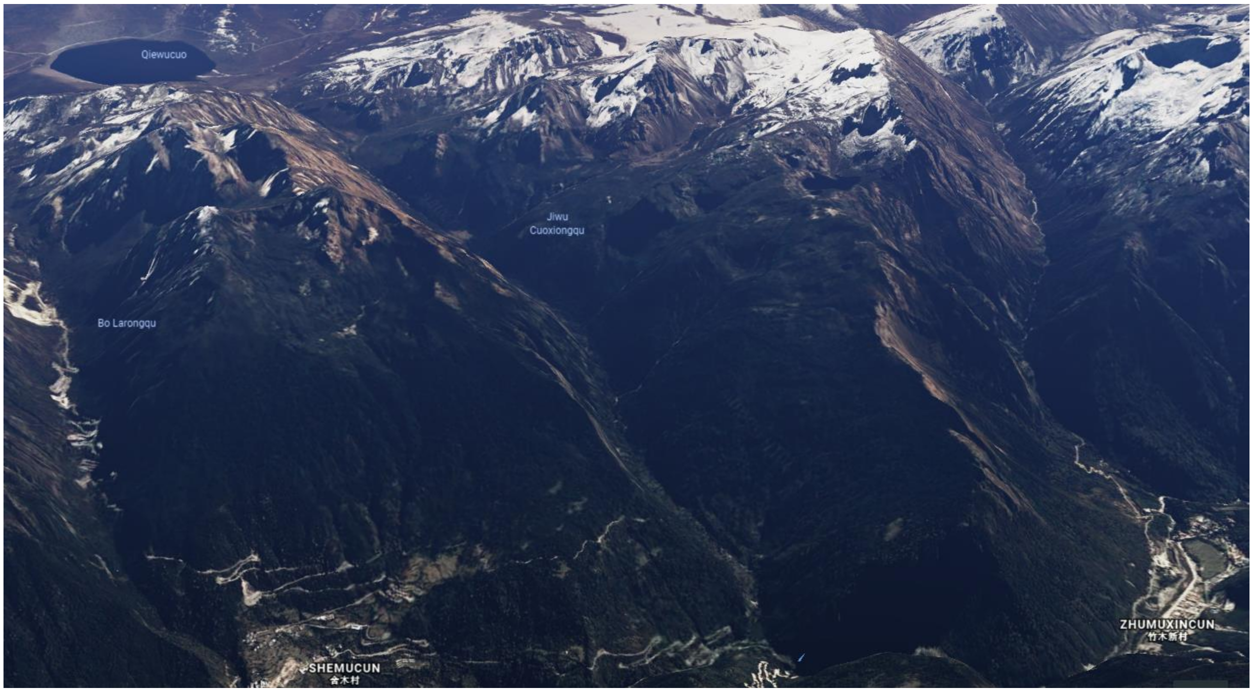

Figure 14. *Google Earth imagery showing a potential PHS site under S2 southeast of Yamdrok Lake. The site's quality is good, with a head of 1117m and a head to distance ratio of 0.14. The feasibility score is 6.0, with three villages at the base of the mountains.*

Figure 15. *Google Earth imagery showing a potential PHS site under S2 southwest of Yamdrok Lake. The site's quality is good, with a head of 771m and a head to distance ratio of 0.15. The feasibility score is 7.4.*

Discussion

Results analysis

The results indicate that the S1 methodology yielded generally unsatisfactory results. In retrospect, the poor quality of S1 results is largely caused by two factors. First, the underlying lake data still contained errors despite it having been manually checked, as many of the marginal sites involved lakes that should have been connected, but the shapefile indicated them as separate lakes. Second, the structure and geometry of some reservoirs on the Tibetan Plateau may be such that converting them to PHS sites would require significant engineering. Figure 12, which is representative of most marginal results under S1, show that lakes on the Tibetan Plateau typically cover large areas with gentle slopes on their banks. The average depth of the lake, as a result, may be shallower than what was assumed in the model (20m). This is important not only from a capacity standpoint but also because a shallow bottom not only makes PHS construction more difficult but also can result in higher evaporation rates due to having an exponentially larger surface area when water levels rise. While it is possible that with engineering (i.e., dams and artificial embankments) these marginal sites can be converted to good PHS sites, it would involve significant disruption to the local hydrology and environment, which this study aims to avoid.

On the other hand, the S2 results yielded much higher quality results despite yielding only two unutilized sites. This is primarily because the use of rivers in the analysis reduced the methodology's dependence on lakes alone. Instead of searching for reservoir pairs, which as discussed above is subject to errors in the underlying data, a search by an existing reservoir for a nearby river significantly decreases the methodology's susceptibility to the errors above. The goal of the study was never about finding the greatest number of sites, but rather finding those of the highest quality. For an initial reconnaissance into possible PHS sites of a region, it is much better therefore to deliver few but high-quality results than multiple marginal ones. Furthermore, the fact that the S2 methodology was able to not only show Yamdrok Lake as one of the three results but also indicate it as the highest capacity of the three was particularly reassuring. It confirmed that the S2 methodology is fundamentally sound.

While the feasibility score map was not used extensively due to the lack of good quality sites, it nevertheless assisted with analyzing the feasibility of the two resulting S2 sites. Both S2 sites had scores above 7, and a holistic Google Earth analysis showed that the southeastern site had multiple villages in its vicinity, which is indicative of economic demand for PHS facilities. However, because of the highly speculative nature of the score map, more data, including grid infrastructure, would need to be factored in. As such, we cannot conclusively determine the strength of the score map as a proxy for feasibility.

Risks and limitations

In addition to errors that exist within the lake data, errors in the underlying DEM data may also exist. A closer examination of sites shows that the elevation on the edges of the lakes often had a slightly higher elevation than the center. This was particularly evident in lakes under S1 and may have resulted in inaccurate head calculations.

This study also assumes that the seasonality and the hydrologic variabilities of lakes in the Tibetan Plateau are factored into the underlying lakes data. However, as we have seen in S1, the exact boundaries of many lakes are inaccurate when compared to Google Earth images. To understand the region's climatic and hydrologic variations more, we attempted to obtain precipitation, evaporation, and prevailing winds data for the region, but the scarcity of the weather stations and the prevalence of mountainous terrain make these meteorological data less meaningful, as in mountainous regions weather is often driven by local factors. An accurate model of on precipitation and evaporation, therefore, would have required a separate GIS-based analysis on the regional climatic and weather patterns.

The calculation of storage capacity is also flawed. Currently, the standard calculation of potential PHS capacity in literature depends solely on the upper reservoir. However, in many cases in S1 the lower reservoir had much less volume, which would have been a limiting factor for capacity assuming no significant engineering and modification. Furthermore, it is very unlikely that an upper reservoir would be completely drained, as doing so would have also involved significant alterations to the local hydrology and ecosystem. In reality, most PHS facilities require an upper and lower limit on water levels. Factoring this into the calculation would involve in significantly more accurate predictions on PHS capacity.

While Google Earth is a cost-effective and time-saving proxy for ground truth assessments, it does not replace them. A ground truth assessment for this study was initially planned but was ultimately canceled due to logistical complications traveling to the highly sensitive region of the TAR. Using Google Earth or other satellite images such as those from Landsat or other high-resolution sensors often offers a good general view of the study area but is ultimately limited by spatial and temporal resolutions needed to make a more confident assessment. We conclude that a ground truth assessment would have resolved the uncertainty for many of the marginal sites in S1.

Many lakes and rivers in Tibet have some forms of spiritual significance to regional religions such as Tibetan Buddhism, Bon, and others. As such, development of PHS facilities in the region may face opposition from the local population. The development of the Yamdrok PHS facility, for example, faced steep opposition from the local Tibetans. With criticism from the Panchen Lama, it was even halted for three years. Interestingly, the Yamdrok project was originally designed as a standard hydropower plant. Its later conversion to a PHS facility was actually a part of the compromise between the Chinese government and the Panchen Lama, who was keenly aware of the many potential environmental consequences from over-draining the lake (CODA, 2015).

Although this study has eschewed discussing the geopolitical risks of the region, we must acknowledge the environmental aspects of such discussion. The Tibetan Plateau has often been referred to as the "Water Tower of Asia," providing more than 85 million m^3 of water annually to almost 3 billion people (Bandyopadhyay, 2013). Altering the hydrology and water flow of rivers with PHS facilities, therefore, may change the water supply patterns of not only Chinese rivers such as the Yangtze, but also those of neighboring countries. India, for example, has vehemently opposed the construction of the Zangmu Hydropower Station, the largest hydropower plant in Tibet with a nameplate capacity of 300 MW on the Yarlung Zangbo River, as it flows through India and becomes the Brahmaputra river (CODA, 2015).

Summary

In conclusion, while PHS site selection should involve a careful analysis of geography, hydrology, environmental impacts, and geology, this study nevertheless serves as an important starting point to not only factor in basic geographical requirements in the construction of PHS facilities in remote regions like Tibet, but also basic infrastructure and economic demand variables such as roads and population density. For the first time in literature, GIS-based analysis involving river-lake scenarios is developed. However, the lack of good quality sites in S1 and the scarcity of sites in S2 may suggest that Tibet may not be as apt for PHS development as was previously thought. Continued analysis and refinement of the methodology are needed.

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References

Bandyopadhyay, J. (2013). Securing the Himalayas as the Water Tower of Asia: An Environmental Perspective. *Asia Policy*, *16*, 45-50.

Barbour, E., Wilson, I. A., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of Pumped Hydro Energy Storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, *61*, 421-432.

Barton, J. P., & Infield, D. G. (2004). Energy storage and its use with intermittent renewable energy. *Transitions on Energy Conversion*, *19*(2), 441-448.

BP. (2018). *BP statistical review of world energy*.

Chang, X., Liu, X., & Zhou, W. (2010). Hydropower in China at present and its further development. *Energy*, *35*(11), 4400-4406.

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, *19*(3), 291-312.

CODA. (2015). Reflections of Electric Power Construction in Tibet. *ChinaGoAbroad*. Retrieved from http://www.chinagoabroad.com/en/article/reflections-of-electric-power-construction-in-tibet

Connolly, D., MacLaughlin, S., & Leahy, M. (2010). Development of a computer program to locate potential sites for pumped hydroelectric energy storage. *Energy*, *35*(1), 375-381.

Evans, A., Strezov, V., & Evans, T. J. (2012). Assessment of utility energy storage options for increased renewable energy penetration. *Renewable and Sustainable Energy Reviews*, *16*(6), 4141-4147.

Fitzgerald, N., Lacal-Arántegui, R., McKeogh, E., & Leahy, P. (2012). A GIS-based model to calculate the potential for transforming conventional hydropower schemes and non-hydro reservoirs to pumped hydropower schemes. *Energy*, *41*(1), 483-490.

Gimeno-Gutiérrez, M., & Lacal-Arántegui, R. (2015). Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. *Renewable Energy*, *75*, 856-868.

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems - Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, *12*(5), 1221-1250.

International Energy Agency (IEA). (2019). *Global energy & co2 status report*.

IPCC. (2019). *Summary for policymakers. Special Report: Global Warming of 1.5 C*.

Larentis, D. G., Collischonn, W., Olivera, F., & Tucci, C. E. M. (2010). GIS-based procedures for hydropower potential spotting. *Energy*, *35*(10), 4237-4243.

Lei, Y., Yao, T., Yang, K., Sheng, Y., Kleinherenbrink, M., Yi, S., . . . Zhang, G. (2017). Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology. *Geophysical research letters*, *44*(2), 892-900.

Liu, G., & Lucas, M. (2014). Invest in renewable energy in Tibet. *Nature*, (514), 35.

Lu, X., & Wang, S. (2017). A GIS-based assessment of Tibet's potential for pumped hydropower energy storage. *Renewable and Sustainable Energy Reviews*, *69*, 1045-1054.

Luo, G.-L., & Guo, Y.-W. (2013). Rural electrification in China: A policy and institutional analysis. *Renewable and Sustainable Energy Reviews*, *23*, 320-329.

Ming, Z., Zhang, K., & Liu, D. (2013). Overall review of pumped-hydro energy storage in China: Status quo, operation mechanism and policy barriers. *Renewable and Sustainable Energy Reviews*, *17*, 35-43.

Popular Science. (1930, July). A Ten-Mile Storage Battery. *Popular Science Monthly*, 60.

US Department of Energy. (2019). Pumped-Storage Hydropower. Retrieved from https://www.energy.gov/eere/water/pumped-storage-hydropower

van der Linden, S. (2006). Bulk energy storage potential in the USA, current developments and future prospects. *Energy*, *31*(15), 3446-3457.

Zeng, M., Feng, J., Xue, S., Wang, Z., Zhu, X., & Wang, Y. (2013). Development of China's pumped storage plant and related policy analysis. *Energy Policy*, *61*, 104-113.